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Review on multi-criteria decision analysis aid in sustainable energy decision-making

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ABSTRACT

Multi-criteria decision analysis (MCDA) methods have become increasingly popular in decision-making for sustainable energy because of the multi-dimensionality of the sustainability goal and the complexity of socio-economic and biophysical systems. This article reviewed the corresponding methods in different stages of multi-criteria decision-making for sustainable energy, i.e., criteria selection, criteria weighting, evaluation, and final aggregation. The criteria of energy supply systems are summarized from technical, economic, environmental and social aspects. The weighting methods of criteria are classified into three categories: subjective weighting, objective weighting and combination weighting methods. Several methods based on weighted sum, priority setting, outranking, fuzzy set methodology and their combinations are employed for energy decision-making. It is observed that the investment cost locates the first place in all evaluation criteria and CO_2 emission follows closely because of more focuses on environment protection, equal criteria weights are still the most popular weighting method, analytical hierarchy process is the most popular comprehensive MCDA method, and the aggregation methods are helpful to get the rational result in sustainable energy decision-making.

Contents

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1. Introduction

Energy including renewable energy and geologic storages is an essential input to all forms of economic and social activities as shown in Fig. 1. Energy system plays an important role in the economic and social development of a country and the living quality of people [1,2]. The major energy demand of fossil fuels has major consequences around the world. A main environmental problem is the emission of toxic chemical pollutants, greenhouse gases like CO_2 and other air pollutants [3,4]. These cause climate change and environmental pollution of air, land and water, which has a negative impact on the health and the living quality of humans [5]. Contrarily, global environmental issues could significantly affect patterns of energy use around the world [6]. Some new governmental policies have been adopted to encourage the introduction of energy efficiency measures, the technical changes, and the renewable and sustainable energy [3,7,8].

The sustainable development has been the subject of wide-ranging discussion and debate within government, non-government and academic circles, being a major focus of national and international economic, social and environmental agendas [3,4,6–18]. Sustainable development means the satisfaction of present needs without compromising the ability of future generations to meet their own needs [19]. Sustainability can be seen as the final goal: a balance of social and economic activities and the environment [9]. A sustainable energy sector has a balance of energy production and consumption and has no, or minimal, negative impact on the environment (within the environmental tolerance limits), but gives the opportunity for a country to employ its social and economic activities.

The rational decision-making (DM) in energy supply system options, planning, management and economy is helpful to the sustainable development. However, the complex interactions shown in Fig. 1 make DM more difficult. Sustainable energy

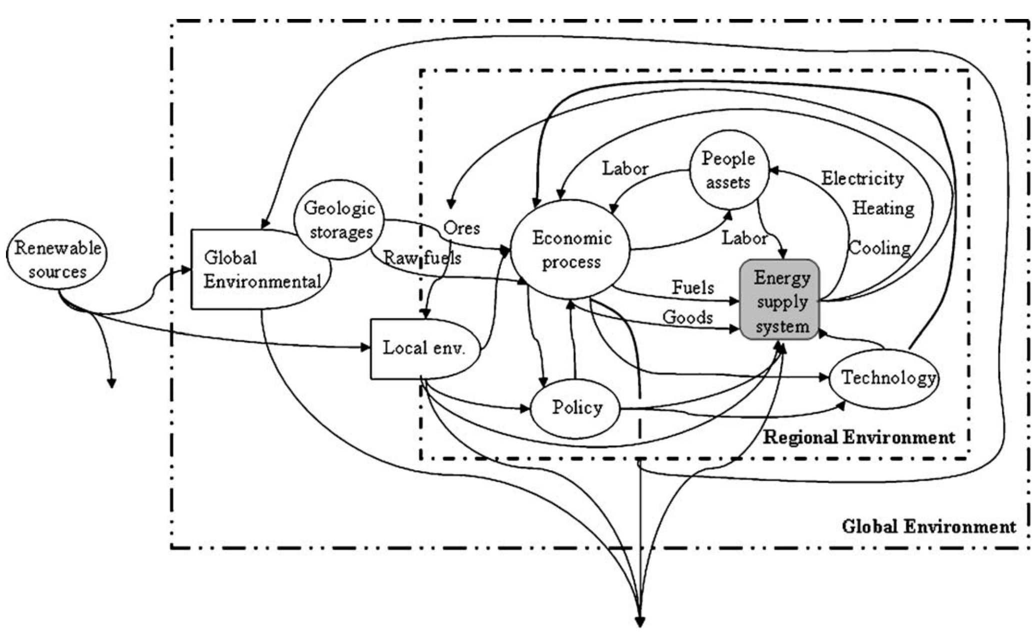

Fig. 1. The complex interactions of energy system.

decision-making using multi-criteria decision analysis (MCDA) just provides a method to eliminate the difficulty and it has attracted the attention of decision makers for a long time. MCDA is a form of integrated sustainability evaluation. It is an operational evaluation and decision support approach that is suitable for addressing complex problems featuring high uncertainty, conflicting objectives, different forms of data and information, multi interests and perspectives, and the accounting for complex and evolving biophysical and socio-economic systems. The methods can provide solutions to increase complex energy management problems. Traditional single criteria approach is normally aimed at identifying the most efficient options at a low cost. Growing environmental awareness in the 1980s has slightly modified the single criteria decision framework. Nowadays, the focus on global environmental protection drives MCDA aid in energy systems. The MCDA methods have been widely applied to social, economic, agricultural, industrial, ecological and biological systems in addition to energy systems [20–27]. Compared to single criteria approach, the distinctive advantage of MCDA methods is to employ multi-criteria or attributes to obtain an integrated DM result.

Generally, the MCDA problem for sustainable energy DM involves m alternatives evaluated on n criteria. The grouped decision matrix can be expressed as follows:

$$\begin{array}{ll} & \begin{array}{cccc} \text{criteria} & C_1 & C_2 & \cdots & C_n \\ (\text{weights} & w_1 & w_2 & \cdots & w_n) \end{array} \\ \text{alternatives} & \text{-- -- -- -- -- --} \\ X = \begin{array}{c} A_1 \\ A_2 \\ \vdots \\ A_m \end{array} & \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{pmatrix}_{m\times n} \end{array} \quad (1)$$

where x_{ij} is the performance of j-th criteria of i-th alternative, w_j is the weight of criteria j, n is the number of criteria and m is the

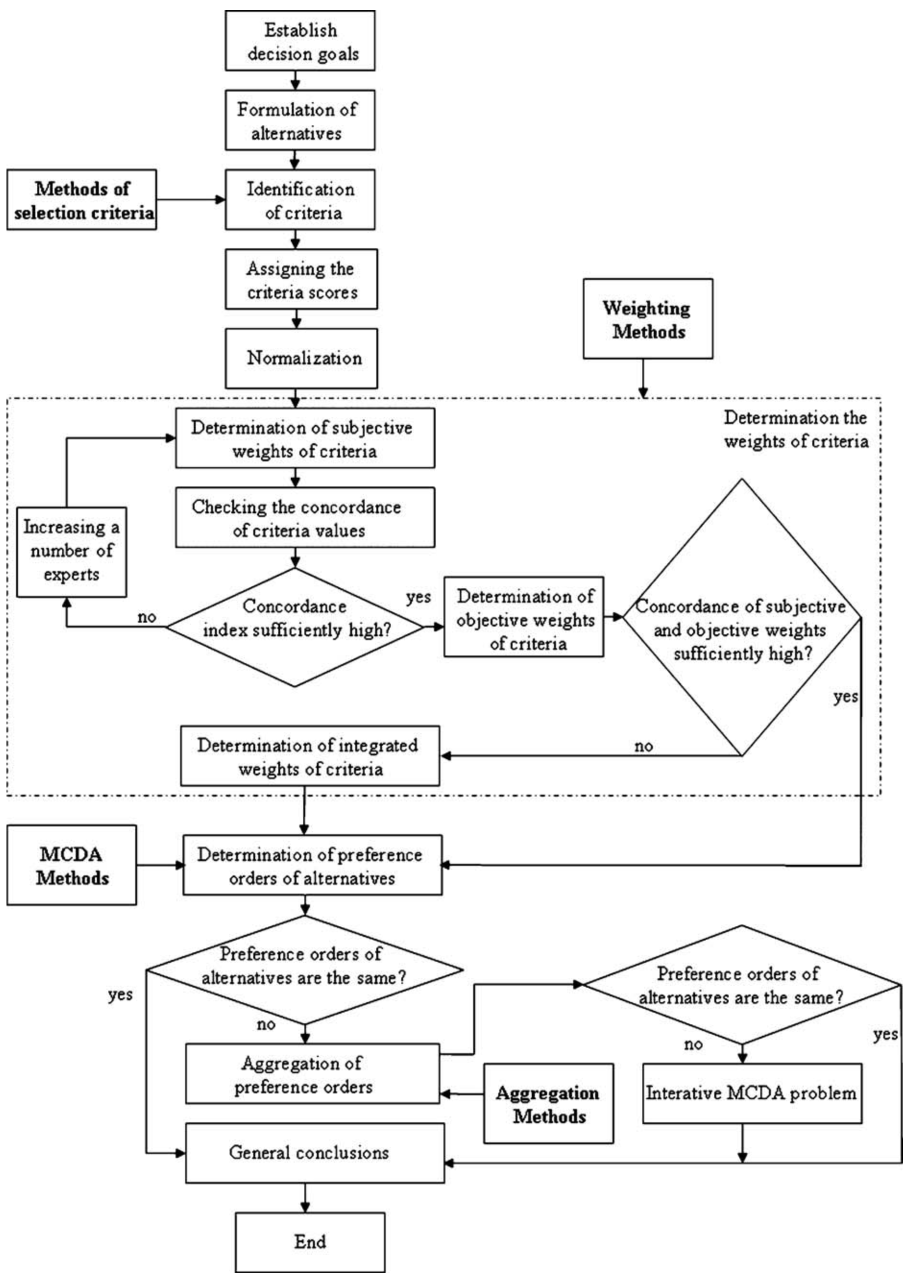

Fig. 2. MCDA process in sustainable energy decision-making.

number of alternatives (these nomenclatures are just the same in this article).

It can be found that the DM problem involves alternatives, criteria, criteria weights and the evaluating result from Eq. (1). The corresponding DM process can be formed to Fig. 2 [28,29]. It usually includes four main stages: alternatives' formulation and criteria selection, criteria weighting, evaluation, and final treatment and aggregation. The preliminary step in MCDA is to formulate the alternatives for sustainable energy DM problem from a set of selected criteria and to normalize the original data of criteria. Secondly, criteria weights are determined to show the relative importance of criteria in MCDA. Then, the acceptable alternatives are ranked by MCDA methods with criteria weights. Finally, the alternatives' ranking is ordered. If all alternatives' ranking orders in different MCDA methods are just the same, the DM process is ended. Otherwise, the ranking results are aggregated again and the best scheme is selected. The four main sections in MCDA are presented and reviewed in Sections 2–5 respectively.

2. Criteria selection

2.1. Literature review on criteria in energy DM

The energy issues applying MCDA includes energy planning and selection [11–13,30–47], energy resource allocation [48–54], energy exploitation [55,56], energy policy [57–59], building energy management [60–67], transportation energy systems [68,69] and others [70–75]. The reviewed literatures covered are both theoretical/conceptual and empirical. This article mainly reviews the MCDA methods for the selection of the energy supply systems. The reviewed articles have different energy supply systems, such as combined heating and power (CHP) or combined cooling heating and power (CCHP) systems [29,76–78], renewable energy systems [35,39], and different focus such as technological, economic and sustainability evaluation, objective and subjective comparison, the impact on the living standard and the sensitivity analysis of power plants, etc. [43,79–81].

Measuring sustainability of the energy supply systems is a major issue as well as a driving force of the discussion on sustainability development. Developing evaluation criteria and methods that reliably measure sustainability is a prerequisite for selecting the best alternative, identifying non-sustainable energy supply system, informing design-makers of the integrated performances of the alternatives and monitoring impacts on the social environment. The multiplicity of criteria and measuring tools being developed in this fast-growing field shows the importance of the conceptual and methodological work in this area. The development and selection of criteria require parameters related to the reliability, appropriateness, practicality and limitations of measurement. The used criteria to evaluate the energy supply systems in the literatures mainly divide to four aspects: technical, economic, environmental and social criteria, which are summarized in Table 1.

2.1.1. Technical criteria

2.1.1.1. Efficiency. Efficiency refers to how much useful energy we can get from an energy source. The efficiency coefficient is the ratio of the output energy to the input energy, which is used to evaluate energy systems. Energy efficiency is said to be one of the "twin pillars" of a sustainable energy policy [93]. It has been proved that efficiency improvement that is consistent with high plant reliability and low-cost of products is economically beneficial [94]. Efficient energy use is essential to slowing the energy demand growth. It is the most used technical criteria to evaluate energy systems [11,13,30,35–44,77,87].

2.1.1.2. Exergy efficiency. Exergy efficiency (also known as the second-law efficiency or rational efficiency) computes the efficiency of a process taking the second law of thermodynamics

Table 1
The typical evaluation criteria of energy supply systems.

Aspects	Criteria	Literatures	Total number
Technical	Efficiency	[11,13,30,35–44,77,87]	15
	Exergy efficiency	[29,44,76]	3
	Primary energy ratio	[29,45,76,82]	4
	Safety	[29,39–42,45,76,83,86]	9
	Reliability	[39–44,80,81,84]	9
	Maturity	[29,82,84]	3
	Others	[13,29,40,41,43,83–85]	–
Economic	Investment cost	[11,13,29,30,35–45,74,76–78,83–87,92]	24
	Operation and maintenance cost	[30,39–44,74,76,84,85,87,92]	13
	Fuel cost	[11,38,40–43,77,78,87]	9
	Electric cost	[30,35–37,77,83,87]	7
	Net present value (NPV)	[29,45,88–90]	5
	Payback period	[13,29,45,88]	4
	Service life	[30,36,76,85]	4
	Equivalent annual cost (EAC)	[29,45,88,91]	4
	Others	[11,39–42,44]	–
Environmental	NO_x emission	[11,29,36–38,45,76,79–81,83,92]	12
	CO_2 emission	[11,29,30,35–38,45,76–85,87,88,92]	21
	CO emission	[29,45,76]	3
	SO_2 emission	[11,38,74,78–81,83]	8
	Particles emission	[78–82]	5
	Non-methane volatile organic compounds (NMVOCs)	[79–81]	3
	Land use	[29,35,36,76,77,80–82,86,87]	10
	Noise	[29,45,76,84–86]	6
	Others	[13,44,74,84,85,90,91]	–
Social	Social acceptability	[78,80,81,84]	4
	Job creation	[13,36,38,80–82,86,89,90]	9
	Social benefits	[13,39–42]	5
	Others	[11,29,40–42,45,76,78,80,82]	–

into account. Energy changes from one form to another during a process. In contrast, exergy accounts for the irreversibility of a process due to increases in entropy. Exergy is always destroyed when a process involves a temperature change. Exergy is the energy that is available to be used. Exergy analysis is performed in the field of industrial ecology to use energy more efficiently, which was first coined by Rant in 1956 [95]. The CHP (CCHP) systems in the literatures were evaluated in these criteria [29,44,76].

2.1.1.3. Primary energy ratio (PER). PER is defined as the ratio of consumption primary energy to the users' demand energy. Similarly primary energy saving is also a criteria that provides an estimation of the amount of primary energy that a given action allows to save. Primary energy saving can be assessed as the annual saved energy, which derives from fossil fuels. Such a saving can be estimated by means of: (1) technologies of conversion which use renewable energy sources or (2) reduction of final energy consumptions, under the same operating conditions. PER was employed to evaluate CCHP systems in [29,45,76] and primary energy saving was adopted to show the performances of renewable energy technologies [82] directly. Also, savings of finite energy sources were used [84].

2.1.1.4. Safety. Continuous changes in technology, environmental regulation and public safety concerns make the analysis of complex safety-critical of energy systems more and more demanding. Safety of energy systems is vital to society, national development and people's life. The basic safety of workers on the site of energy project is guaranteed first. Safety is often seen as one of a group of related disciplines: quality, reliability, availability, maintainability and safety. The criteria are specifically defined when sustainable energy DM. Safety can be a technical evaluation criteria of applied technology and also a social criteria to show their effects of energy systems to society and people, etc. [29,39–42,45,76,83,86].

2.1.1.5. Reliability. Reliability of energy systems may be defined to the capacity of a device or system to perform as designed; the resistance to failure of a device or system; the ability of a device or system to perform a required function under stated conditions for a specified period of time; or the ability of something to "fail well" (fail without catastrophic consequences). Reliability has always been a concern in the energy sector. Some factors and events are heightening concern about energy reliability, such as political tensions, high profile terrorist activity, and massive blackouts [96–98]. The quality of the equipment, its maintenance, the type of fuel, the design of the energy system and how it is operated play a great role in its reliability. Reliability of energy systems is one among the essential criteria for their evaluations [39–44,80,81,84]. It can be expressed in a qualitative scale or a number, such as realization time in [84].

2.1.1.6. Maturity. Technical maturity is a criteria to evaluate the applied technology of energy systems [29,82,84]. Measuring the degree of maturity of the technology can refer how widespread the technology is at both national and international level. In detail, the following stages can be considered: (1) technologies that are only tested in laboratory; (2) technologies that are only performed in pilot plants, where the demonstrative goal is linked to the experimental one, referring to the operating and technical conditions; (3) technologies that could be still improved; and (4) consolidated technologies, which are close to reaching the theoretical limits of efficiency.

Additionally, there are some particular criteria reflecting the technology of energy systems or equipments. The capacity of a power plant (it is defined to the amount of electricity that it produces over a period, divided by the amount of electricity it could have produced if it had run at full power over that period) was selected to evaluate its ability [43,83–85]. Availability of fuel was applied to [40,41] evaluate fossil fuel, solar energy, wind energy, hydro-electric and nuclear power plants. Also the ability to respond to peak load was employed to assess alternative scenarios for the power generation sector in Greece [83]. Regulation and control properties were used to reflect its technical performance [29] and knowledge of the innovative technology was employed to show its development [13]. The reserves-to-production ratio calculates the availability (in years) of a certain type of fuel according to current consumption and the annual consumption increase/decrease the rate of each non-renewable energy source for electric power generation [43].

2.1.2. Economic criteria

2.1.2.1. Investment cost. Investment cost comprises of all costs relating to: the purchase of mechanical equipment, technological installations, construction of roads and connections to the national grid, engineering services, drilling and other incidental construction work. Labor costs or costs for the equipment maintenance are not included in investment costs. Nuclear and coal-fired units are characterized by high investment costs and low operating costs while gas-fired generation is characterized by lower capital costs and higher operating costs. The investors must consider the investment costs and the benefit. Investment cost is the most used economic criteria to evaluate energy systems [11,13,29,30,35–45,74,76–78,83–87,92].

2.1.2.2. Operation and maintenance cost. Operation and maintenance costs consist of two parts. One is the operation cost that includes employees' wages, and the funds spent for the energy, the products and services for the energy system operation. Another is the maintenance cost that aims to prolong energy system life and avoid failures that may lead to its operation suspension. The funds spent for maintenance are less than the financial damage obtained from an energy system failure and increase the credibility and confidence index of the energy system. The operation and maintenance costs are also divided into two subcategories: fixed and variable costs. Operation and maintenance cost is another most used economic criteria [30,39–44,74,76,84–86,92].

2.1.2.3. Fuel cost. Fuel cost refers to the fund spent for the provision of raw material necessary (i.e. uranium for nuclear power plants) for energy supply system operation. Fuel costs may include extraction or mining, transportation and possible fuel processing to be used in a power plant. Fuel costs may vary considerably in different time periods and areas as a result of several reasons, including demand, production and policy matters. The fuel is the essential input in energy system as shown in Fig. 1. Some researchers adopted fuel cost to evaluations [11,38,40–43,77,78,87]. Especially, it is notable that the fuel cost excludes from operation cost when fuel cost and operation and maintenance cost are both selected to evaluations.

2.1.2.4. Electric cost. Electric cost, which is the product cost of power plant, was seen as a criteria to evaluate its economic performance from the viewpoint of consumers [30,35–37,77,83,87]. Governments, investors, producers and consumers have different expectation on the electric cost. It is necessary to evaluate the electric cost of different energy systems rationally.

2.1.2.5. Net present value (NPV). NPV, also called as net present worth (NPW), is defined as the total present value of a time series of cash flows. It is a standard method for using the time value of

money to appraise long-term energy projects. Used for capital budgeting, and widely throughout economics, it measures the excess or shortfall of cash flows, in present value terms, once financing charges are met. NPV is often used to assess its feasibility of an energy project by investor. It is also necessarily considered in early stage of energy DM [29,45,88–90].

2.1.2.6. Payback period. Payback period of an energy project refers to the period of time required for the return on an investment to "repay" the sum of the original investment. It intuitively measures how long something takes to "pay for itself"; shorter payback periods are obviously preferable to longer payback periods to investor [13,29,45,88]. Although primarily a financial term, the concept of a payback period is occasionally extended to energy payback period (the period of time over which the energy savings of a project equal the amount of energy expended since project inception).

2.1.2.7. Service life. An energy system's service life is its expected lifetime, or the acceptable period of use in service. Generally, the energy system tire's life follows the bathtub curve, to boot. After installation, there is a not-small probability of failure. Then, the tire will perform, given no defect-introducing event such as encountering a road hazard (a nail or a pothole), for a long duration relative to its expected service life. After a period, the failure probability will rise again. Contrarily to payback period, longer service life is preferable to investor and it was employed to select the best scheme from energy system alternatives [30,36,76,85].

2.1.2.8. Equivalent annual cost (EAC). Equivalent annual cost of energy project is the cost per year of owning and operating an asset over its entire lifespan. EAC is often used as a decision-making tool in capital budgeting when comparing investment projects of unequal lifespan. EAC is calculated by dividing the NPV of an energy project by the present value of an annuity factor. Some works employed EAC as an evaluation criteria [29,45,88,91].

Expect these criteria, the special criteria were applied to MCDA. In some literatures, there were not specific environmental criteria to be used while the definite cost criteria were converted due to the environmental protection, such as CO_2 emission avoided [44] and environmental constraints cost [39–42].

2.1.3. Environmental criteria

2.1.3.1. NO_x emission. NO_x is a generic term for mono-nitrogen oxides (NO and NO_2). NO_x comprise a group of molecules that can contribute to local air pollution, acid deposition and global climate change. NO_x also readily reacts with ammonia, moisture, volatile organic compounds, common organic chemicals, and even ozone, to form a wide variety of toxic products which may damage the health of people and cause biological mutations. Consequently, they have a direct impact on the health of the community and an indirect impact on the social state of the community. NO_x is produced during the combustion of fossil fuels and biomass, especially combustion at high temperatures. The NO_x emission of energy system is popularly selected to evaluate its performances [11,29,36–38,45,76,79–81,83,92].

2.1.3.2. CO_2 emission. CO_2 is a colorless, odorless and tasteless gas that is about one and a half times as dense as air under ordinary conditions of temperature and pressure. It was reported that CO_2 contributes 9–26% to the greenhouse effect [99]. CO_2 is mainly released through the combustion of coal/lignite, oil and natural gas in energy systems. The disafforestation in the world lessen the removal of atmospheric CO_2 by photosynthesis and also contributes to the greenhouse effect. Different energy systems have different CO_2 emissions. For example, new technology combining cycles burning natural gas can save practically 33% of CO_2 emissions with regard to conventional cycles. CO_2 leads to the global warming, which is focused by many governments, academies, and researchers. Naturally, CO_2 emission of energy system is certainly a criteria to evaluate its sustainability [11,29,30,35–38,45,76–85,87,88,92].

2.1.3.3. CO emission. CO is produced from the partial combustion of carbon-containing compounds, notably in internal-combustion engines. Through natural processes in the atmosphere, it is eventually oxidized to carbon dioxide. Carbon monoxide has an atmospheric lifetime of only a few months [51] and as a consequence is spatially more variable than longer-lived gases. Likewise, anthropogenic CO from automobile and industrial emissions may contribute to the greenhouse effect and global warming. In literatures [29,45,76] CO emission was selected to characterize the performances of the energy systems.

2.1.3.4. SO_2 emission. SO_2 is another harmful gaseous emission of coal/lignite, oil and combined cycle natural gas power plants. Further oxidation of SO_2 forms H_2SO_4 and thus acid rain [100], which is one of the causes for concern over the environmental impact of the use of these fuels as power sources. SO_2 is also associated with increased respiratory symptoms and disease, difficulty in breathing, and premature death. SO_2 can be chemically bound in flue gas desulfurization and the U.S. has witnessed a 33 percent decrease in emissions between 1983 and 2002. However, the cost is considerable. Consequently the environment-friendly energy systems need higher operation costs necessarily. SO_2 emission can be selected to evaluate its contribution to environment [11,38,74,78–81,83].

2.1.3.5. Particles emission. Particles emissions to the atmosphere are also one of the main environmental problems of the energy industries. These emissions are mainly released by coal/lignite and oil as well as biomass and photovoltaic power plants (during their cell construction). Fine particles formed in the atmosphere by the conversion of SO_2 and NO_x emissions scatter light and create hazy conditions, decreasing visibility and contributing to regional haze. Particles emission is also a worst type of emission for human health. The risk for human health depends on size, distribution, microstructure and chemical composition of particulate released into the atmosphere [80]. The particle size and type, etc, depends on the fuel of energy systems [101–103] so that some energy systems were evaluated in the criteria, particles emission [78–82].

2.1.3.6. Non-methane volatile organic compounds (NMVOCs). NMVOC is a generic term for a large variety of chemically different compounds, like for example, benzene, ethanol, formaldehyde, cyclohexane, or acetone. Essentially, NMVOCs are identical to volatile organic compounds (VOCs), but with methane excluded. Sometimes NMVOC is also used as a sum parameter for emissions, where all NMVOC emissions are added up per weight into one figure. In the absence of more detailed data, this can be a very coarse parameter for pollution, e.g. for summer smog or indoor air pollution. Chatzimouratidis and Pilavachi selected NMVOCs to evaluate the power plants [43,79–81].

2.1.3.7. Land use. Energy system occupies some land. The land required by each plant is a matter of great concern for their evaluation [29,35,36,76,77,80–82,86,87]. The environment and landscape are affected directly by the land occupied by energy systems. Land use can also be a social criteria to evaluate the energy system. It represents one of the most critical factors for the intervention site, especially where the human activities are

relevant factors of environmental pressure [82]. Quality of people's life is affected by energy systems as it could have been used for the creation of parks and recreation centers. The excavations, tunnels and other work necessary for energy systems operation destabilize the flora, the fauna and the ecosystem in general. Different energy systems occupy different land while the products are same. Particularly energy supply systems with biomass and biofuels require the large amount of land. Land use is necessarily considered to energy DM.

2.1.3.8. Noise. Noise pollution from energy systems is displeasing machine-created sound that disrupts the activity or balance of human or animal life. It not only leads to the environmental effects, but also damage physiological and psychological health of human. Especially, chronic exposure to noise in working area of energy plants may cause noise-induced hearing loss. Noise can be an environmental criteria or social criteria to evaluate energy systems [29,45,76,84–86].

Additionally, some particular, pertinent and distinctiveness criteria reflecting the energy systems' contributions to environment were used. For instance, depletion of abiotic resources human toxicity, ecotoxicity, photo-oxidant formation and eutrophication were used for natural gas energy solutions evaluation [44]. Visual impact reflects the visual nuisance that may be created by the development of an energy project in a specific area and it was used for evaluating the various wind energy plant alternatives proposed [84].

Except for these idiographic criteria, there are some recapitulative criteria in the sustainable energy decision-making, such as effects on natural environment [13,74,85,90], climate change [13,44,86,91] and acidification [44,91]. These criteria do not characterize the performances or contributions in only numerical data or aspect. For example, Both NO_x emission and SO_2 emission contribute acid rain while acidification including the two criteria is used to evaluate energy systems.

2.1.4. Social criteria

Social aspects were definitely the most important criteria for people's acceptance of energy systems during the past decades. Table 4 summarizes the key social criteria of energy supply systems in the literature.

2.1.4.1. Social acceptability. Social acceptability expresses the overview of opinions related to the energy systems by the local population regarding the hypothesized realization of the projects under review from the consumer point of view. It is extremely important since the opinion of the population and of pressure groups may heavily influence the amount of time needed to go ahead with and complete an energy project. Social acceptance is not expressed as a measurable figure. It is not a quantitative criteria but a qualitative one. Qualitative measures of alternatives against the criteria can be obtained according to the results of the survey carried out in the local community or city. Social acceptability was employed to analyze their feasibilities of CHP, renewable energy power plants, etc. [78,80,81,84].

2.1.4.2. Job creation. Energy supply systems employ many people during their life cycle, from construction and operation till decommissioning. The energy systems are closely related to the society shown in Fig. 1. Local societies where energy systems were established based their development and prosperity on them for many decades. The sustainable energy system creating more jobs for people is beneficial to improve the living quality of local peoples [80]. In the DM process of local governments, job creations of energy systems are indispensably considered and are selected to evaluate their contributions [13,36,38,80–82,86,89,90].

2.1.4.3. Social benefits. Social benefits were definitely the most important criteria for people's life during the past decades. The criteria express the social progress in the local regions by introducing an energy project, especially in the less developed regions. Social benefit is also a qualitative criteria and not expressed as a measurable figure. The criteria is a recapitulative criteria, but some actual items can express it, such as job creations, social life and income generation [104]. Social benefits were directly used to aid in the sustainable energy DM [13,39–42].

Furthermore, some researchers have employed some particular and recapitulative criteria aid in sustainable energy DM. National economy was introduced to evaluate the contributions of the energy systems to national economy and social development [40–42]. Health social criteria were applied to select the best CHP alternative in Croatia because the NO_x emission of energy systems has a direct impact on the health of the community [78]. Also compensation rate aims at restoring people's degradation of quality of life and was used to assess power plants [80]. Energy use per household, share of household income spent on fuel and electricity, number of injured per energy produced and number of working hours per energy produced were used to analyze five scenarios of sustainable energy systems in Belgrade [11]. Compatibility with political, legislative and administrative framework was adopted to decide the diffusion of renewable energy technology with regard to government support, the tendency of institutional actors, and the policy of public information [82]. Advanced performance and maintenance convenience were used to show their contributions of the energy technologies to social development [29,45,76].

2.2. Methods of criteria selection

There are various criteria to show the performance of energy system. It is not absolute that more and more criteria are helpful to the sustainable energy decision-making. Likewise, less criteria are beneficial to the evaluation of energy systems. Furthermore, there are repeatability and relevancy in the criteria system, such as the inclusion of fuel cost in operation and maintenance cost, and job creations and social benefits of energy project. Generally, the following principles are obeyed to select the "major" criteria used to energy decision-making [105,106]:

(1) *Systemic principle*. The criteria system should roundly reflect the essential characteristic and the whole performance of the energy systems. The comprehensive evaluation function of multi-criteria can obtain better results than the sum of single criteria evaluations.
(2) *Consistency principle*. The criteria system should be consistent with the DM objective.
(3) *Independency principle*. The criteria should not have inclusion relationship at the same level criteria. The criteria should reflect the performance of alternatives from different aspects.
(4) *Mensurability principle*. The criteria should be measurable in quantitative value as possible or qualitatively expressed.
(5) *Comparability principle*. The DM result is more rational when the comparability of criteria is more obvious. Additionally, the criteria should be normalized to compare or operate directly when there are both benefit criteria and cost criteria.

These principles give the instruction to the decision-makers to select criteria. However, these principles are difficult to follow and some "minor" criteria may be chosen. Therefore it is necessary that some rational methods are applied to select the "major" criteria, distinguish the main and secondary and construct the reasonable criteria systems. The following elementary selection methods of criteria used to sustainable energy DM are introduced:

2.2.1. Delphi method

The Delphi method is a systematic and interactive method, which relies on a panel of independent experts [105–107]. Delphi is based on the principle that forecasts from a structured group of experts are more accurate than those from unstructured groups or individuals [108]. The carefully selected experts answer questionnaires for criteria selection to evaluate energy systems in two or more rounds. After each round, the summaries of the experts' selection from the previous round as well as the reasons they provided for their judgments are fed back to the experts. Thus, participants are encouraged to revise their earlier answers in light of the replies of other members of the group. It is believed that during this process the range of the selected criteria will decrease and the group will converge towards the "correct" criteria. Finally, the process is stopped after a pre-defined stop criteria (e.g. number of rounds, achievement of consensus, and stability of results). Delphi has been widely used in social, ecological and economic works. Similarly, Delphi method can also be applied in the weighting and evaluation in the latter Sections 3 and 4.

2.2.2. Least mean square (LMS) method

The principle of LMS method is that one criteria contributes less importance to results and it can be ignored when its performances of alternatives are almost same or near although the criteria is vital in evaluation [105,107]. To lessen its relativity with other criteria, the criteria can be removed. Let

$$s_j = \sqrt{\frac{1}{m}\sum_{i=1}^{m}(x_{ij}-\bar{x}_j)^2} \quad (j = 1, 2, \ldots, n) \tag{2}$$

where x_{ij} is the i-th sample of the j-th criteria, $i = 1, 2, \ldots, m$, and $\bar{x}_j = (1/m)\sum_{i=1}^{m} x_{ij}$.

If there exists k to make $s_k = \min_{1 \le j \le n}\{s_j\}$ and $s_k \approx 0$, the k criteria that corresponds to s_k can be removed. This method can be also used to elicit the selected weights in Section 3 (the m alternative in the selected n criteria form to the new group decision matrix and then the calculated standard deviation in Eq. (2) again is normalized to get the weights).

2.2.3. Minmax deviation method

Minmax deviation method is similar to LMS method [105,107]. The judgment standard is the deviation values of criteria. The maximum deviation of criteria x_j can be calculated as

$$r_j = \max_{1 \le i,l \le m}\{|x_{ij} - x_{lj}|\} \tag{3}$$

Likewise, if there exists k to make $r_k = \min_{1 \le j \le n}\{r_j\}$ and $r_k \approx 0$, the k criteria that correspond to r_k can be removed. Similarly, This method can be also used to elicit weights.

2.2.4. Correlation coefficient method

Correlation analysis adopts the correlation coefficient to show the interaction between criteria. The correlation coefficient between criteria C_i and criteria C_j can be calculated as

$$r_{ij} = \frac{cov(C_i, C_j)}{\delta_{C_i}\delta_{C_j}} \tag{4}$$

where $\mathrm{cov}(C_i,C_j)$ is the covariance of C_i and C_j, and δ_{C_i} and δ_{C_j} are the standard deviation of C_i and C_j respectively.

The correlation coefficients between n criteria can form to a $n \times n$ matrix, $R_{n\times n}$. When $r_{ij} = 1$, criteria C_i are completely related to criteria C_j. However, the correlation coefficient includes more or less influence because other criteria are not constant. To reflect the interaction well, the partial correlation coefficient is considered to determine the interaction between criteria and computed as

$$\xi_{ij} = \frac{-R_{ij}}{\sqrt{R_{ii}R_{jj}}} \tag{5}$$

where R_{ij}, R_{ii} and R_{jj} are algebraic complements of elements, r_{ij}, r_{ii} and r_{jj}, in matrix $R_{n\times n}$. Greater the partial correlation coefficient is, more correlative the two criteria. When $\xi_{ij} = 1$, criteria C_i is completely related to criteria C_j and one of the two criteria can be removed.

Based on the elementary methods, some specific methods were developed and extended to various complex systems, such as grey relational method [109,110], analytic hierarchy process (AHP) [111,112], clustering method [105], principal component analysis [113] and rough set method [110]. The principle of all selection methods is to eliminate the relevance between criteria and select the independent criteria. Grey relational method and AHP are also MCDA methods applied to get the ranking order of energy systems alternatives and the detailed introduction can be found in Section 4 of this article.

3. Weighting methods

All factors have their internal impact reclassified to a common scale so that it is necessary to determine each criteria's relative impact in the sustainable energy DM problem. Weight is assigned to the criteria to indicate its relative importance. Different weights influence directly the DM results of energy systems' alternatives. Consequently, it is necessary to obtain the rationality and veracity of criteria weights. Three factors are usually considered to obtain the weights: the variance degree of criteria, the independency of criteria, and the subjective preference of the decision-makers.

Generally there are two methods: the equal weights and the rank-order weights [114]. The methods have been both applied in sustainable energy DM shown in Table 2.

(1) Equal weights method

The criteria weight in equal weights method is defined as

$$w_i = \tfrac{1}{n}, \quad i = 1, 2, \ldots, n, \tag{6}$$

The method requires minimal knowledge of the decision-maker's priorities and minimal input from decision maker. The

Table 2
The reviewed weighting methods for sustainable energy DM.

Categories	Weighting methods		Literatures	Total number
Equal weights	–		[30,35–38,44,54,78,83,91]	10
Rank-order weights	Subjective	AHP	[33,41–43,57,79–81]	8
		Simos	[32,82,86]	3
		Pair-wise comparison	[29,39,40,60,74,76,87]	7
		Priority given to one indicator with others being the same	[30,35–38,54,78]	7
		Others	[11,13,55,85,89,90]	–
	Objective	Entropy method	[60,76,87]	3
	Combination	Additive synthesis	[76,79,87]	3

equal weights method was popularized and applied in many decision-making problems since Dawes and Corrigan argued that this method often produced the results nearly as good as those optimal weighting methods in 1974 [115]. Equal weights method is the most popular in sustainable energy DM [30,35–38,44,54,78,83,91].

(2) Rank-order weighting method

The equal weights method has also been criticized because it ignores the relative importance among criteria. Following this argument, the rank-order weighting method was proposed and criteria weights are distributed as

$$w_1 \geq w_2 \geq \cdots \geq w_n \geq 0 \tag{7}$$

where $\sum_{i=1}^{n} w_i = 1$.

The rank-order weighting methods are classified into three categories: subjective weighting method, objective weighting method and combination weighting method. Criteria weights determined by the subjective weighting methods depend only on the preference of decision-makers, not on the quantitative measured data of energy projects. Contrarily, the objective weights are obtained by mathematical methods based on the analysis of the initial data. The subjective weighting methods explain the evaluation clearly while the objectivity ones are relatively weak. Additionally, the judgments of decision-makers sometimes absolutely depend on their knowledge or information. Thus, the criteria weights' errors in some extent are unavoidable. As we can see, none of the two approaches is perfect. It may be suggested that an integrated method could be most appropriate for determining the criteria weights. Currently, a number of combination or optimal weighting methods were proposed and developed.

The weighting stage in Fig. 2 also displays the process that combined three weighting categories. First, the subjective weights are determined by experts and the concordance of criteria values is checked by the decision-maker. When the concordance index is not sufficiently high, more experts are needed to modify the subjective weights to get the high concordance. Then, the objective weights of criteria are calculated in measured data. Finally, the concordance of subjective and objective weights is checked in a similar way. If the concordance cannot get satisfied, the combination methods are applied to determine the integrated weights of criteria.

Table 3 summarizes the weighting methods in the MCDA DM [105,107,116,117]. The basic and representative methods are presented in this article and other methods can be found detailedly in others referred literatures.

Table 3
Weighting methods in MCDA DM.

Categories	Weighting methods	
Subjective weighting	Simple multi-attribute rating technique (SMART)	
	SMARTER	
	Swing	
	Trade-off	
	SIMOS	
	Pair-wise comparison	
	AHP	
	Least-square method	
	Eigenvector method	
	Delphi method	
	Consistent matrix analysis	
	PATTERN	
Objective weighting	Least mean square (LMS) method	
	Minmax deviation method	
	Entropy method	
	TOPSIS method	
	Vertical and horizontal method	
	Variation coefficient	
	Multi-objective optimization method	
	Multiple correlation coefficient	
	Principal component analysis	
Combination weighting	Multiplication synthesis	
	Additive synthesis	Optimal weighting based on sum of squares
		Optimal weighting based on minimum bias
		Optimal weighting based on relational coefficient of gradation

3.1. Subjective weighting methods

Subjective weighting methods such as pair-wise comparison [29,39,40,60,74,76,87], AHP [33,41–43,57,79–81] and Simos [32,82,86], were the most used methods in sustainable energy DM. Especially, priority given to one indicator with others being the same was employed to protrude the performances in one aspect in literatures [30,35–38,54,78]. The following part introduces briefly several representative subjective weighting methods.

3.1.1. Simple multi-attribute rating technique (SMART)

SMART was originally described as the whole process of rating alternatives and weighting criteria by Edwards in 1977 [118]. The participants are asked to rank the importance of the changes in the criteria from the worst criteria levels to the best levels. Then they assign 10 points to the least important criteria, and increasing number of points (without explicit upper limit) are assigned to the other criteria to address their importance relative to the least important criteria. The weights are calculated by normalizing the sum of the points to one. Edwards and Barron listed the shortcomings, stressed that weights should clearly be related to the criteria ranges in 1994 [119] and presented an improved version, SMARTER. The idea of SMARTER is to use the centroid method so that the weight of a criteria ranked to be ith is

$$w_i = \frac{1}{n}\sum_{k=i}^{n}\frac{1}{k} \tag{8}$$

3.1.2. SWING

With the SWING weighting method [114,120], the decision maker begins by rank ordering criteria in terms of their associated value ranges. First the respondent is asked to select the criteria that he would most prefer to change from its worst to its best level and to assign 100 points to this most important criteria. Then the respondent is continued to choose the criteria change from the worst to the best level which he considers to be the second most desirable improvement and to assign points less than 100 to that criteria change. Proceeding in this fashion, the decision maker ranks all criteria and assigns relative importance points to their value ranges. Finally the given points are normalized to sum up to one to get the criteria weights. The SWING method is an algebraic, decomposed, direct procedure.

3.1.3. SIMOS

The main innovation in this approach proposed by Simos in 1990 [121] consists of associating a "playing card" with each criteria. The participants are asked to rank these cards (or criteria) from the least important to the most important. The rank order of a

criteria expresses the importance a single participant wants to ascribe to that criteria: the first criteria in the ranking is the least important and the last criteria in the ranking is the most important. If the two criteria are found to be equally important, these are given the same rank position. In order to allow participants to express strong preference between criteria, another set of cards (white cards) is introduced. The participants are asked to introduce white cards between two successive colored cards, while the number of white cards is proportional to the difference between the importance of the considered criteria. Subsequently, the criteria weights are calculated using the rank positions attributed in the previous step: the rank positions are simply divided by the total sum of the positions of the considered criteria, thus providing a vector of weights to be applied to the evaluation criteria, in the form of real values summing up to 1.

3.1.4. Pair-wise comparison

In the pair-wise comparison method, participants are presented a worksheet and are asked to compare the importance of two criteria at a time: "Which one of these two criteria is more important, and how much more important?" Then the relative importance is scored. The scales can be various, for example, a scale of 0 (equal importance) to 3 (absolutely more important) is commonly adopted. The results are consolidated by adding up the scores obtained by each criteria when preferred to the criteria it is compared with. The results are then normalized to a total of 1.0. This weighting method provides a framework for comparing each criteria against all others, and helps to show the difference in importance between criteria. However, it does not allow you to check the consistency of participants' preferences, especially, their transitivity. You should therefore examine the results' matrices for each participant to check for major problems.

3.1.5. AHP

AHP method builds on the pair-wise comparison model for determining the weights for every unique criteria. AHP was proposed primarily by Saaty in 1980 [122,123]. The matrix of pair-wise comparisons when there are n criteria at a given level can be formed as:

$$D = \begin{bmatrix} C_1/C_1 & C_1/C_2 & \cdots & C_1/C_n \\ C_2/C_1 & C_2/C_2 & \cdots & C_2/C_n \\ \vdots & \vdots & \ddots & \vdots \\ C_n/C_1 & C_n/C_2 & \cdots & C_n/C_n \end{bmatrix} \quad (9)$$

The relative importance can be scaled in Table 4. Based on the matrix, criteria weights can be calculated in some methods, such as arithmetic mean method, characteristic root method, and least square method [124]. Because individual judgments will never agree perfectly, the degree of consistency achieved in the pair-wise comparison is measured by a consistency ratio indicating whether the comparison made is sound.

3.2. Objective weighting methods

The objective weighting method elicits the criteria weights using the measurement data and information and reflects the difference degree. The literatures about objective weighting methods applied in sustainable energy DM are seldom in the reviewed published papers while the objective weighting methods were widely applied to other evaluation systems, such as social and ecological systems. Only entropy method was employed to elicit the weights [60,76,87] in energy projects. The typical objective weighting methods are presented as follows.

3.2.1. Entropy method

The entropy shows that how much the criteria reflects the information of system and how great the uncertainty of criteria is. A vector of $x_j = (x_{1j}, x_{2j}, \cdots, x_{mj})$ characterizes the set X in terms of the i-th criteria, defined as follows:

$$X_j = \sum_{i=1}^{m} x_{ij}, \quad j = 1, 2, \ldots, n \quad (10)$$

Then the entropy measure of j-th criteria contrast intensity is

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^{m} \frac{d_{ij}}{D_j} \ln \frac{d_{ij}}{D_j} \quad (11)$$

Finally, the normalized weights can be calculated as

$$w_j = \frac{1 - e_j}{\sum_{j=1}^{n} (1 - e_j)} \quad (12)$$

3.2.2. Technique for order preference by similarity to ideal solution (TOPSIS) method

The principle of TOPSIS [126] is that the selected best alternative should have the shortest distance from the positive ideal solution in geometrical sense. The weighted distance between alternative A_i and the ideal solution A^* is defined as follows:

$$h_i = \sum_{j=1}^{n} w_j^2 (x_{ij} - x_j^*)^2 \quad (13)$$

Then the following optimal model is solved and the weights can be elicited.

$$\left.\begin{aligned} &\min \sum_{i=1}^{m} h_i = \sum_{i=1}^{m} \sum_{j=1}^{n} w_j^2 (x_{ij} - x_j^*)^2 \\ &s.t. \sum_{j=1}^{n} w_j = 1, \quad w_j \geq 0 \end{aligned}\right\} \quad (14)$$

3.2.3. Vertical and horizontal method

Vertical and horizontal method is also an optimal weighting method. The weights can be solved from the optimal mathematic

Table 4
The AHP pair-wise comparison scale [125].

Intensity of weight	Definition	Explanation
1	Equal importance	Two criteria contribute equally to objectives
3	Weak/moderate importance of on over another	Experience and judgment slightly favored one criteria over another
5	Essential or strong importance	Experience and judgment strongly favor one criteria over another
7	Very strong or demonstrated importance	A criteria is favored very strongly over another; its dominance demonstrated in practice
9	Absolute importance	The evidence favoring one criteria over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent scale values	Used to represent compromise between the priorities listed above
Reciprocals of above non-zero number		If criteria i has one of the above non-zero numbers assigned to it when compared to criteria j, then j has the reciprocal value when compared with criteria I

Table 5
The reviewed MCDA methods for sustainable energy DM.

Categories	MCDA methods	Literatures	Total number
Elementary	Weighted sum	[11,35–38,54,71,73,77,78]	10
Unique synthesizing criteria	AHP	[30,33,41–43,49,50,52,57,74,79–81]	13
	Fuzzy set methodology	[13,26,29,39,40,55,60,72,84,127]	10
	Grey relational method	[45,60,76,87]	4
Outranking	Preference ranking organization method for enrichment evaluation (PROMETHEE)	[55,83,86,89,90]	5
	Elimination et choice translating reality (ELECTRE)	[32,46,47,65,66,75,82,88,90]	9
Others	NAIADE	[44,84]	2
	MACBETH	[85]	1
	Preference assessment by imprecise ratio statements (PAIRS)	[91]	1

model as:

$$\left.\begin{aligned} &\max s_x^2=\sum_{i=1}^{m}(z_i-\bar{z})^2/m \\ &s.t.\sum_{j=1}^{n}w_j^2=1,\quad w_j\geq 0 \end{aligned}\right\} \tag{15}$$

where $z_i=\sum_{j=1}^{n}w_jx_{ij}$ and $\bar{z}=(1/m)\sum_{i=1}^{m}z_i$.

TOPSIS method and vertical and horizontal method both reflect the difference of alternatives' whole performances as possible, while LMS method, minmax deviation method and entropy method reflect the criteria relative importance based on the difference of alternatives to a criteria. In another word, TOPSIS method and vertical and horizontal method base on the integrated evaluation values while other methods base on the difference of single criteria.

3.3. Combination weighting methods

Combination weighting methods were gradually applied to the evaluation and comparison of complex systems, including energy projects [76,79,87]. The methods have two basic combinations: multiplication synthesis and additive synthesis. The principle of multiplication synthesis is expressed as

$$w_j=\frac{w_{1j}w_{2j}}{\sum_{j=1}^{n}w_{1j}w_{2j}} \tag{16}$$

where w_{1j}, w_{2j} and w_j are subjective weight, objective weight and combination weight of the jth criteria respectively.

While the additive synthesis is written as

$$w_j=kw_{1j}+(1-k)w_{2j} \tag{17}$$

where k is the linear combination coefficient and $k\geq 0$.

The combination coefficient can be determined by various methods, such as optimization based on sum of squares, minimum bias and relational coefficient of gradation. For example, the linear combination coefficient was solved in Jaynes maximal entropy theory and the optimization method and the criteria weights were obtained to be used to select the best CCHP scheme from alternatives [76].

4. Multi-criteria decision analysis methods

It is the turn to determine the preference orders of alternative after determining the criteria weights so that MCAD methods are employed to get the ranking order in Eq. (1). In the referred literatures, the listed MCDA methods in Table 5 were mainly applied in all kinds of sustainable energy DM problems [11,13,29,30,32,33,35–47,49,50,52,54,55,57,60,65,66,71–91], such as the selection of CCHP alternatives, the comparisons of renewable energy plants and the DM of energy policy.

Table 6 also summaries all related MCDA methods that are divided into three categories: elementary methods, methods in unique synthesizing criteria and outranking methods. An overview of several typical MCDA methods in energy systems is provided here. A more detailed analysis of the theoretical foundations of theses methods can be found in [106,107,124,128] and/or other references.

4.1. Elementary methods

The elementary methods in Table 6 includes ten methods, the former three methods are defined as non-preference information methods without decision maker, and other methods are multi-attribute information methods with decision maker. Conjunctive and disjunctive methods belong to screening methods that the acceptable alternative must exceed given performance thresholds for all criteria. Lexicographic, elimination by aspects and linear assignment method are ordinal partiality methods. The latter two methods need the criteria preference of decision maker.

4.1.1. Weighted sum method (WSM)

WSM is the most commonly used approach in sustainable energy systems [11,35–38,54,71,73,77,78]. The score of an

Table 6
MCDA methods.

Categories	Weighting methods
Elementary	Dominance Maximin Maximax Conjunctive Disjunctive Lexicographic Elimination by aspects Linear assignment Weighted additive Weighted product
Unique synthesizing criteria	Analytical hierarchy process (AHP) TOPSIS SMART Grey relational analysis Data envelopment analysis Multi-attribute value theory (MAVT) Multi-attribute utility theory (MAUT) Utility theory additive (UTA) Fuzzy weighted sum Fuzzy maximum
Outranking	ELECTRE I, IS, II, III, IV, TRI PROMETHEE I, II ORESTRE

alternative is calculated as

$$S_i = \sum_{j=1}^{n} w_j x_{ij}, \quad i = 1, 2, \ldots, m \tag{18}$$

Then the resulting cardinal scores for each alternative can be used to rank, screen, or choose an alternative. The best alternative is the one whose score is the maximum.

4.1.2. Weighted product method (WPM)

The WPM is similar to WSM. The main difference is that instead of addition in the calculation there is multiplication. The score of alternative i can be calculated as:

$$S_i = \prod_{j=1}^{n} x_{ij}^{w_j}, \quad i = 1, 2, \ldots, m \tag{19}$$

Naturally, the alternative having the maximum score is the best scheme. Because of the exponent property, this method requires all ratings be greater than 1. For example, when a criteria has fractional ratings, all ratings in that criteria are multiplied by 10^m to meet this requirement. Alternative scores obtained by the weighted product method do not have a numerical upper bound. The decision maker may also not find any true meaning in those scores. Hence, it may be convenient to compare each alternative score with the standard score. If an alternative is compared to the ideal alternative for the only comparison purpose, the ratio is given by

$$R_i = \frac{S_i}{S^*} = \frac{\prod_{j=1}^{n} x_{ij}^{w_j}}{\prod_{j=1}^{n} (x_j^*)^{w_j}}, \quad i = 1, 2, \ldots, m \tag{20}$$

where x_j^* is the most favorable performance for criteria j. It is found clearly that the preference of alternative i increases when R_i approaches to 1.

4.2. Unique synthesizing criteria methods

4.2.1. AHP

AHP is widely used for practical MCDA method in various domains, such as social, economic, agricultural, industrial, ecological and biological systems, in addition to energy systems [30,33,41–43,49,50,52,57,74,79–81]. It is a descriptive decision analysis methodology that calculates ratio-scaled importance of alternatives through pair-wise comparison of evaluation criteria and alternative. It involves decomposing a complex decision into a hierarchy with goal (objective) at the top of the hierarchy, criteria and sub-criteria at levels and sub-levels of the hierarchy, and decision alternatives at the bottom of the hierarchy.

AHP is a type of weighted sum method. The weights obtained in AHP method are introduced in Section 3.1. After obtaining the weights, each performance at the given level is then multiplied with its weight and then the weighted performances are summed to get the score at a higher level. The procedure is repeated upward for each hierarchy, until the top of the hierarchy is reached. The overall weights with respect to goal for each decision alternative is then obtained. The alternative with the highest score is the best alternative.

4.2.2. TOPSIS

TOPSIS is used as a weighting method in Section 3. Likewise, it can also be seen as a MCDA method. TOPSIS [126] is based on the concept that the ideal alternative has the best level for all criteria, whereas the negative ideal is the one with all the worst criteria values [29]. The principle is simple: the selected best alternative should have the shortest distance from the positive ideal solution in geometrical sense while it has the longest distance from the negative solution. The method assumes that each criteria has a monotonically increasing or decreasing utility. This makes it easy to locate the ideal and negative ideal solutions.

The positive distance between alternative A_i and the ideal solution A^+ is defined as follows:

$$s_i^+ = \sqrt{\sum_{j=1}^{n} (x_{ij} - x_j^+)^2} \tag{21}$$

where x_j^+ is the jth criteria's performance of the ideal solution A^+.

The negative distance is similarly calculated as follows:

$$s_i^- = \sqrt{\sum_{j=1}^{n} (x_{ij} - x_i^-)^2} \tag{22}$$

where x_j^- is the j-th criteria's performances of the negative ideal solution A^-.

Finally, the relative closeness degree of A_i and A^+ is defined to:

$$r_i = \frac{s_i^-}{s_i^- + s_i^+} \tag{23}$$

The best alternative is one that has the maximum closeness degree and has the shortest distance to the ideal solution.

4.2.3. Grey relation method

Grey relational method is a branch of grey systems theory developed in 1980 [129] and has been largely applied to MCDA problems in addition to energy systems [45,60,76,87]. The principle of grey relation method is similar to TOPSIS. The grey relation degree is defined in the method to show the closeness between the alternatives. Usually, the ideal solution is defined and the alternatives' relation degree with it are calculated. The grey relational coefficient of the jth criteria between alternative A_i and the ideal solution A^* can be calculated as:

$$a(A_j^*, A_{ij}) = \frac{\min_j \min_i |x_j^* - x_{ij}| + \xi \max_j \max_i |x_j^* - x_{ij}|}{|x_j^* - x_{ij}| + \xi \max_j \max_i |x_j^* - x_{ij}|} \tag{24}$$

where x_j^* is the most favorable performance for criteria j, ξ is the distinguishing coefficient, $0 < \xi < 1$, $\min_j \min_i |x_j^* - x_{ij}|$ is secondary smallest error of A_i and A^*, and $\max_j \max_i |x_j^* - x_{ij}|$ is secondary biggest error.

Then the grey relational degree is equal to the weighted sum of its grey relational coefficients. The alternative with the maximum relation degree has shortest distance from the ideal solution while it has the longest distance from the worst solution. Thus the best alternative is selected according to the grey relation degree.

4.2.4. MCDA combined fuzzy methodology

The classic MCAD methods generally assume that all criteria and their respective weights are expressed in crisp values and, thus, that the rating and the ranking of the alternatives can be carried out without any problem. In a real-world decision situation, the application of the classic multi-criteria evaluation methods may face serious practical constraints from the criteria perhaps containing imprecision or vagueness inherent in the information. Due to the availability and uncertainty of information as well as the vagueness of human feeling and recognition, like "equally", "moderately", "strongly", "very strongly", "extremely" and a "significant degree", it is relatively difficult to provide exact numerical values for the criteria, make an exact evaluation and convey the feeling and recognition of objects for decision makers. Hence most of the selection parameters cannot be given precisely and the evaluation data of the alternative suppliers' suitability for various subjective criteria and the weights of the criteria are usually expressed in linguistic terms by the decision makers.

Furthermore, it is also recognized that human judgment on qualitative criteria is always subjective and thus imprecise.

Fuzzy set theory introduced by Zadeh in 1965 [130] can just solve the problem and it play a significant role in this kind of decision situation. The combination of MCDA methods and fuzzy set theory [131] has been applied in many systems in addition to energy systems [13,26,29,39,40,55,60,72,84,127].

4.3. The outranking methods

The foundation of the outranking methods is the construction and the exploitation of an outranking relation that is introduced by Roy. An outranking relation is a binary relation S defined on the set of alternatives A such that for any pair of alternatives $(A_i, A_k) \in A \times A : A_i S A_k$ if, given what is known about the preferences of the decision maker, the quality of the evaluations of the alternatives and the nature of the problem under consideration, there are sufficient arguments to state that the alternative A_i is at least as good as the alternative A_k, while at the same time no strong reason exists to refuse this statement.

Compared to the other multi-criteria evaluation methods, the outranking methods have the characteristic of allowing incomparability between alternatives. This characteristic is important in situations where some alternatives cannot be compared for one or another reason.

4.3.1. Elimination et choice translating reality (ELECTRE) method

Elimination et choice translating reality (ELECTRE) method was proposed by Benayoun, Roy and Sussman in 1966 and it was developed and improved by Roy in 1971 [132–135]. Up to now, ELECTRE families have included ELECTRE I, II, III, IV, TRI and some improved ELECTRE methods. For most ELECTRE methods, there are two main stages. These are the construction of the outranking relations and the exploitation of these relations to get the final ranking of the alternative. Different ELECTRE methods may be different in how they define the outranking relations between alternatives and how they apply these relations to get the final ranking of the alternatives.

ELECTRE concentrates the analysis on the dominance relations among the alternatives. The basic concept of ELECTRE is how to deal with outranking relation by using pair-wise comparisons among alternatives under each criteria separately. It is based on the study of outranking relations, exploitation notions of concordance. These outranking relations are built in such a way that it is possible to compare alternatives. It uses concordance, discordance indexes and threshold values to analyze the outranking relations among the alternatives. The concordance index for a pair of alternatives A_i and A_k measures the strength of the hypothesis that alternative A_i is at least as good as alternative A_k. There are no unique measures of concordance. In ELECTRE II, the concordance index $C(A_i,A_k)$ for each pair of alternatives (A_i,A_k) is defined as follows:

$$C(A_i, A_k) = \frac{\sum_{j \in Q(A_i,A_k)} w_j}{\sum_{j=1}^{n} w_j} \tag{25}$$

where $Q(A_i,A_k)$ is the set of criteria for which A_i is equal of preferred to (i.e., at least as good as) A_k, and w_j is the weight of the jth criteria.

The discordance index $D(A_i,A_k)$ is defined as follows:

$$D(A_i, b) = \frac{\max_{j \in Q'(A_i,b)} |x_{bj} - x_{A_i j}|}{\max_{j=1}^{n} |x_{bj} - x_{A_i j}|} \tag{26}$$

where x_{aj} and x_{bj} represent the performances of alternative A_i and A_k in terms of criteria j respectively, $Q'(A_i,A_k)$ is the set of criteria for which A_i is worse than A_k, and n is the number of criteria. The formula can be only used when the scores for different criteria are comparable.

After computing the concordance and discordance indices for each pair of alternatives, the graphs for strong and weak relationship can be painted respectively by comparing these indices with the threshold values. Then these graphs are employed to obtain two complete preorders based on descending and ascending distillation chains. Finally, the comparison of the two complete preorders is used to elaborate the final ranking order of alternatives.

ELECTRE methods are sometimes unable to identify the preferred alternative, and in this case, they produce a core of leading alternatives. Such methods have been widely used in energy DM [32,46,47,65,66,75,82,88,90]. ELECTRE methods are particularly convenient when encountering a few criteria with a large number of alternatives in a DM problem.

4.3.2. Preference ranking organization method for enrichment evaluation (PROMETHEE)

PROMETHEE method developed by Brans [136] has been used in energy planning and applications, such as geothermal energy project [83,89] renewable energy [86,90] energy exploitation [55]. This method uses the outranking principle to rank the alternatives, combined with the ease of use and decreased complexity. It is well adapted to problems where a finite number of alternatives are to be ranked considering several, sometimes-conflicting criteria. The principle is the construction and the exploitation of a valued outranking relation π. Two complete preorders can be obtained by ranking the alternatives according to their incoming flow and their outgoing flow. The intersection of these two preorders yields the partial preorder of PROMETHEE I where incomparabilities are allowed. The ranking of the alternatives according to their net flow yields the complete preorder of PROMETHEE II.

Like to ELECTRE method, it also performs a pair-wise comparison of alternatives in order to rank them with respect to a number of criteria. However, ELECTRE method only pay attention to the preference and ignore the difference level between alternatives when determining the ranking order. PROMETHEE introduces the preference functions to measure the difference between two alternatives for any criteria. Brans have offered six generalized criteria functions including usual criteria, quasi criteria, criteria with linear preference, level criteria, criteria with linear preference and indifference, and Gaussian criteria.

Multi-criteria preference index for a pair of alternatives A_i and A_k is defined as

$$\pi(A_i, A_k) = \frac{\sum_{j=1}^{n} w_j\, p_j(A_i, A_k)}{\sum_{j=1}^{n} w_j} \tag{27}$$

where $p_j(a,b)$ is the preference functions for alternatives a and b.

Then the incoming flow is calculated as:

$$\phi^{+}(A_i) = \sum_{k=1}^{m} \pi(A_i, A_k), \quad k = 1, 2, \ldots, m \tag{28}$$

and the outgoing flow is calculated as

$$\phi^{-}(A_i) = \sum_{k=1}^{m} \pi(A_k, A_i), \quad k = 1, 2, \ldots, m \tag{29}$$

Finally, the net flow is equal to the difference of incoming flow and outgoing flow. After obtaining all net flows of alternatives, the alternative having maximum net flow is considered as the best.

5. Aggregation methods

Usually, the decision maker selects the best alternative based on the ranking orders after the calculation in a selected MCDA method. However, the creditability of DM is necessarily verified so

that the results of the ranking orders are computed by a few MCDA methods sometimes. The application of various MCDA methods of calculation may yield different results (preference ranking order). The question "Which method is most suitable to solve the problem?" is most important, but difficult to answer. Therefore, the ranking results are necessarily aggregated again and the best scheme from the alternatives is selected as displayed in Fig. 2. The methods used to aggregate the preference orders are called as aggregation methods in this article. In the reviewed papers, there are few consideration on about aggregation methods in energy DM while the aggregation methods were applied in social and economic systems [107]. The aggregation methods can be divided into two categories: voting method and mathematical aggregation method. The mathematical aggregation methods are classified to two sub-categories, "hard aggregation method" and "soft aggregation method" based on with or without the decision-makers.

5.1. Voting methods

A very general approach to aggregating alternatives' preferences is the voting methods. The winning alternative in voting methods depends on which voting rule is used. Generally, Borda rule and Copeland rule [137] are the most common voting rules.

5.1.1. Borda

Borda rule is to select the option that on average stands highest in the voters' rankings. Firstly, assign points to the m alternatives in the individual preferences, namely $m-1$ points for the top ranked alternative, $m-2$ points for the second ranked alternative, down to 0 points for the bottom ranked alternative; then add up those points over all individuals for every alternative; Finally the more points an alternative receives the higher ranked it is in the social preference.

5.1.2. Copeland

Copeland rule is to select the option (if one exists) that beats each other option in exhaustive pair-wise comparison. Firstly, calculate the number of alternatives it beats by a majority and the number of alternatives it looses against for each alternative; then calculate the difference between the two numbers; finally, the larger the number the higher ranked is the alternative in the social preference.

5.2. Mathematical aggregation methods

5.2.1. Hard aggregation methods

"Hard aggregation methods" mean that the aggregating results cannot require the decision-maker and are obtained in mathematical methods over the ranking orders of alternatives, which avoid the preference of decision-makers. The aggregating results have strong objectivity and the selected scheme is compelling. The basic aggregation method is the average method and the developed aggregation methods include vertical and horizontal aggregation method, and singular value decomposition aggregation method. The principle of vertical and horizontal aggregation method is similar to the method in Section 3.2.3 and it is also an optimal method based on the ranking orders or the evaluation scores of alternatives. The singular value decomposition aggregation method has been employed to analyze the feasibility of combination weighting method for criteria of CHP [87] and the principle applied to aggregation of ranking orders is same.

5.2.2. Soft aggregation methods

"Soft aggregation methods" require the decision-maker and the final results are obtained through the negotiation of decision-makers when there are difference or collision of opinion. The method embodies the flexible decision that makes the majority of decision-makers satisfied. The "soft aggregation methods" are more seldom in practical application. Yi et al. proposed the aggregation methods treating the multi-evaluation conclusions characterized by disagreement [138] and conflict [139].

6. Conclusion

A review of the published literature on sustainable energy decision-making presented here indicates greater applicability of MCDA methods in changed socio-economic scenario and leads to the following conclusions:

(1) Multi-attributes considered in the sustainable energy decision-making gains increasing popularity. It can be observed that efficiency, investment cost, CO_2 emission and job creation are the most common criteria in the technical, economic, environmental and social attributes respectively. The investment cost locates the first place in all evaluation criteria and CO_2 emission follows closely because of more focuses on environment protection.
(2) Criteria weights influence directly the decision-making results of energy projects' alternatives. Equal criteria weights are still the most popular in weighting methods. AHP method in the rank-order weighting method is more and more prevalent because of its understandability in theory and the simplicity in application. The objective and combination weighting methods rise in the decision-making gradually. They will be largely applied to sustainable energy decision-making because they evaluate the relative importance objectively without decision-makers.
(3) MCDA methods have been widely employed to sustainable energy decision-making considering multi-criteria. It is observed that AHP is the most popular comprehensive method so that the elementary weighted sum method is still basic in multi-criteria decision-making problems. Fuzzy set methodology has been increasingly applied to take care of the qualitative criteria and the imprecision or vagueness inherent in the information.
(4) The evaluation and calculation in the sustainable energy decision-making is usually obtained in a MCDA method. It is necessary that a few different styles of MCDA methods are applied to get the ranking orders of energy projects' alternatives and the validity in MCDA methods is verified. It is believed that the results obtained by the aggregation methods are more rational and more aggregation methods will aid in the sustainable energy decision-making in the future.

As long as criteria selection and weights, MCDA methods and aggregation methods are appropriate and suitable to the specific decision problems, MCDA can become a powerful tool for the decision-making of sustainable energy systems.

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References

[1] Yuan J-H, Kang J-G, Zhao C-H, Hu Z-G. Energy consumption and economic growth: evidence from China at both aggregated and disaggregated levels. Energy Economics 2008;30:3077–94.
[2] Soytas U, Sari R. Energy consumption and income in G-7 countries. Journal of Policy Modeling 2006;28:739–50.
[3] Bilgen S, Keles S, Kaygusuz A, SarI A, Kaygusuz K. Global warming and renewable energy sources for sustainable development: a case study in Turkey. Renewable and Sustainable Energy Reviews 2008;12:372–96.

[4] Omer AM, Energy. environment and sustainable development. Renewable and Sustainable Energy Reviews 2008;12:2265–300.
[5] Fung WY, Lam KS, Hung WT, Pang SW, Lee YL. Impact of urban temperature on energy consumption of Hong Kong. Energy 2006;31:2623–37.
[6] Yüsel I. Hydropower in Turkey for a clean and sustainable energy future. Renewable and Sustainable Energy Reviews 2008;12:1622–40.
[7] Abulfotuh F. Energy efficiency and renewable technologies: the way to sustainable energy future. Desalination 2007;209:275–82.
[8] Resnier M, Wang C, Du P, Chen J. The promotion of sustainable development in China through the optimization of a tax/subsidy plan among HFC and power generation CDM projects. Energy Policy 2007;35:4529–44.
[9] Hofman K, Li X. Canada's energy perspectives and policies for sustainable development. Applied Energy 2009;86:407–15.
[10] Pereira Jr AO, Soares JB, de Oliveira RG, de Queiroz RP. Energy in Brazil: toward sustainable development? Energy Policy 2008;36:73–83.
[11] Jovanovic M, Afgan N, Radovanovic P, Stevanovic V. Sustainable development of the Belgrade energy system. Energy 2009;34:532–9.
[12] McDowall W, Eames M. Towards a sustainable hydrogen economy: a multi-criteria sustainability appraisal of competing hydrogen futures. International Journal of Hydrogen Energy 2007;32:4611–26.
[13] Doukas HC, Andreas BM, Psarras JE. Multi-criteria decision aid for the formulation of sustainable technological energy priorities using linguistic variables. European Journal of Operational Research 2007;182: 844–55.
[14] Alam S, Fatima A, Butt MS. Sustainable development in Pakistan in the context of energy consumption demand and environmental degradation. Journal of Asian Economics 2007;18:825–37.
[15] Vera I, Langlois L. Energy indicators for sustainable development. Energy 2007;32:875–82.
[16] Blinc R, Zidansek A, Slaus I. Sustainable development and global security. Energy 2007;32:883–90.
[17] Kinrade P. Toward a sustainable energy future in Australia. Futures 2007;39:230–52.
[18] Klevas V, Streimikiene D, Grikstaite R. Sustainable energy in Baltic States. Energy Policy 2007;35:76–90.
[19] WCED. WCoEaD, our common future. Melbourne: Oxford University Press; 1987
[20] Chang N-B, Parvathinathan G, Breeden JB. Combining GIS with fuzzy multi-criteria decision-making for landfill siting in a fast-growing urban region. Journal of Environmental Management 2008;87:139–53.
[21] Qin XS, Huang GH, Chakma A, Nie XH, Lin QG. A MCDM-based expert system for climate-change impact assessment and adaptation planning—a case study for the Georgia Basin, Canada. Expert Systems with Applications 2008;34:2164–79.
[22] Chou C-C. A fuzzy MCDM method for solving marine transshipment container port selection problems. Applied Mathematics and Computation 2007;186: 435–44.
[23] Farahani RZ, Asgari N. Combination of MCDM and covering techniques in a hierarchical model for facility location: a case study. European Journal of Operational Research 2007;176:1839–58.
[24] Kwak NK, Lee CW, Kim JH. An MCDM model for media selection in the dual consumer/industrial market. European Journal of Operational Research 2005;166:255–65.
[25] Ehrgott M, Klamroth K, Schwehm C. An MCDM approach to portfolio optimization. European Journal of Operational Research 2004;155:752–70.
[26] Lee SK, Mogi G, Kim JW, Gim BJ. A fuzzy analytic hierarchy process approach for assessing national competitiveness in the hydrogen technology sector. International Journal of Hydrogen Energy 2008;33:6840–8.
[27] Özelkan EC, Duckstein L. Analysing water resources alternatives and handling criteria by multi criterion decision techniques. Journal of Environmental Management 1996;48:69–96.
[28] Ustinovichius L, Zavadskas EK, Podvezko V. Application of a quantitative multiple criteria decision making (MCDM-1) approach to the analysis of investments in construction. Control and Cybernetics 2007;36:251–68.
[29] Wang J-J, Jing Y-Y, Zhang C-F, Shi G-H, Zhang X-T. A fuzzy multi-criteria decision-making model for trigeneration system. Energy Policy 2008;36:3823–32.
[30] Pilavachi PA, Stephanidis SD, Pappas VA, Afgan NH. Multi-criteria evaluation of hydrogen and natural gas fuelled power plant technologies. Applied Thermal Engineering 2009;29:2228–34.
[31] Buchholz T, Rametsteiner E, Volk TA, Luzadis VA. Multi criteria analysis for bioenergy systems assessments. Energy Policy 2009;37:484–95.
[32] Georgopoulou E, Lalas D, Papagiannakis L. A multicriteria decision aid approach for energy planning problems: the case of renewable energy option. European Journal of Operational Research 1997;103:38–54.
[33] Aras H, Erdogmus S, Ko E. Multi-criteria selection for a wind observation station location using analytic hierarchy process. Renewable Energy 2004;29:1383–92.
[34] Voropai NI, Ivanova EY. Multi-criteria decision analysis techniques in electric power system expansion planning. International Journal of Electrical Power & Energy Systems 2002;24:71–8.
[35] Afgan NH, Carvalho MG. Multi-criteria assessment of new and renewable energy power plants. Energy 2002;27:739–55.
[36] Afgan NH, Carvalho MG. Sustainability assessment of hydrogen energy systems. International Journal of Hydrogen Energy 2004;29:1327–42.
[37] Afgan NH, Carvalho MG. Sustainability assessment of a hybrid energy system. Energy Policy 2008;36:2903–10.
[38] Begic F, Afgan NH. Sustainability assessment tool for the decision making in selection of energy system—Bosnian case. Energy 2007;32:1979–85.
[39] Mamlook R, Akash BA, Nijmeh S. Fuzzy sets programming to perform evaluation of solar systems in Jordan. Energy Conversion and Management 2001;42:1717–26.
[40] Mamlook R, Akash BA, Mohsen MS. A neuro-fuzzy program approach for evaluating electric power generation systems. Energy 2001;26:619–32.
[41] Akash BA, Mamlook R, Mohsen MS. Multi-criteria selection of electric power plants using analytical hierarchy process. Electric Power Systems Research 1999;52:29–35.
[42] Mohsen MS, Akash BA. Evaluation of domestic solar water heating system in Jordan using analytic hierarchy process. Energy Conversion and Management 1997;38:1815–22.
[43] Chatzimouratidis AI, Pilavachi PA. Technological, economic and sustainability evaluation of power plants using the Analytic Hierarchy Process. Energy Policy 2009;37:778–87.
[44] Dinca C, Badea A, Rousseaux P, Apostol T. A multi-criteria approach to evaluate the natural gas energy systems. Energy Policy 2007;35:5754–65.
[45] Huang Fu Y, Wu JY, Wang RZ, Huang XH. Study on comprehensive evaluation model for combined cooling heating and power system (CCHP). Journal of Engineering Thermophysics 2005;26:13–6.
[46] Madlener R, Antunes CH, Dias LC. Assessing the performance of biogas plants with multi-criteria and data envelopment analysis. European Journal of Operational Research 2009;197:1084–94.
[47] Barda OH, Dupluis J, Lencoini P. Multicriteria location of thermal power plants. European Journal of Operations Research 1990;45:32–346.
[48] Ramanathan R, Ganesh LS. Multi-objective analysis of cooking-energy alternatives. Energy 1994;19:469–78.
[49] Ramanathan R, Ganesh LS. Energy resource allocation incorporating quantitative and qualitative criteria: an integrated model using goal programming and AHP. Socio Economic Planning Sciences 1995;29:197–218.
[50] Ramanathan R, Ganesh LS. A multi-objective programming approach to energy resource allocation problems. International Journal of Energy Research 1990;17.
[51] Wu Z, Wei Z. Mitigation assessment results and priorities for China's energy sector. Applied Energy 1997;56:237–51.
[52] Hobbs BF, Horn GTF. Building public confidence in energy planning: a multi-method MCDM approach to demand side planning at BC gas. Energy Policy 1997;25:357–75.
[53] Chedid R, Mezher T, Jarrouche C. A fuzzy programming approach to energy resource allocation. International Journal of Energy Research 1999;23:303–17.
[54] Afgan NH, Pilavachi PA, Carvalho MG. Multi-criteria evaluation of natural gas resources. Energy Policy 2007;35:704–13.
[55] Goumas M, Lygerou V. An extension of the PROMETHEE method for decision making in fuzzy environment: Ranking of alternative energy exploitation projects. European Journal of Operational Research 2000;123:606–13.
[56] Georgopoulou E, Sarafidis Y, Diakoulaki D. Design and implementation of a group DSS for sustaining renewable energies exploitation. European Journal of Operational Research 1998;109:483–500.
[57] Kablan MM. Decision support for energy conservation promotion:: an analytic hierarchy process approach. Energy Policy 2004;32:1151–8.
[58] Greening LA, Bernow S. Design of coordinated energy and environmental policies: use of multi-criteria decision-making. Energy Policy 2004;32:721–35.
[59] Diakoulaki D, Zopounidis C, Mavrotas G, Doumpos M. The use of a preference disaggregation method in energy analysis and policy making. Energy 1999;24:157–66.
[60] Wang J-J, Zhang C-F, Jing Y-Y, Zheng G-Z. Using the fuzzy multi-criteria model to select the optimal cool storage system for air conditioning. Energy and Buildings 2008;40:2059–66.
[61] Wright JA, Loosemore HA, Fermani R. Optimization of building thermal design and control by multi-criterion genetic algorithm. Energy and Buildings 2002;34:959–72.
[62] D'Cruz NA, Radford AD. Multi-criteria model for building performance and design. Building and Environment 1987;22:167–79.
[63] Klemm K, Marks W, Klemm AJ. Multicriteria optimization of the building arrangement with application of numerical simulation. Building and Environment 2000;35:537–44.
[64] Marks WM. Multicriteria optimization of shape of energy-saving buildings. Building and Environment 1997;32:331–9.
[65] Blondeau P, Spérandio M, Allard F. Multicriteria analysis of ventilation in summer period. Building and Environment 2002;37:165–76.
[66] Roulet CA, Flourentzou F, Labben HH, Santamouris M, Koronaki I, Dascalaki E, et al. ORME: A multicriteria rating methodology for buildings. Building and Environment 2002;37:579–86.
[67] Le Teno JF, Mareschal B. An interval version of PROMETHEE for the comparison of building products' design with ill-defined data on environmental quality. European Journal of Operational Research 1998;109:522–9.
[68] Brand C, Mattarelli M, Moon D, Wolfler Calvo R, STEEDS:. A strategic transport-energy-environment decision support. European Journal of Operational Research 2002;139:416–35.
[69] Yedla S, Shrestha RM. Multi-criteria approach for the selection of alternative options for environmentally sustainable transport system in Delhi. Transportation Research Part A Policy and Practice 2003;37:717–29.
[70] Shackley S, McLachlan C. Trade-offs in assessing different energy futures: a regional multi-criteria assessment of the role of carbon dioxide capture and storage. Environmental Science & Policy 2006;9:376–91.

[71] Patlitzianas KD, Ntotas K, Doukas H, Psarras J. Assessing the renewable energy producers' environment in EU accession member states. Energy Conversion and Management 2007;48:890–7.
[72] Ben Salah C, Chaabene M, Ben Ammar M. Multi-criteria fuzzy algorithm for energy management of a domestic photovoltaic panel. Renewable Energy 2008;33:993–1001.
[73] Renn O. Social assessment of waste energy utilization scenarios. Energy 2003;28:1345–57.
[74] Chattopadhyay D, Ramanathan R. A new approach to evaluate generation capacity bids.. IEEE Transactions on Power Systems 1998;13:1232–7.
[75] Neves LP, Martins AG, Antunes CH, Dias LC. A multi-criteria decision approach to sorting actions for promoting energy efficiency. Energy Policy 2008;36: 2351–63.
[76] Wang J-J, Jing Y-Y, Zhang C-F, Zhang X-T, Shi G-H. Integrated evaluation of distributed triple-generation systems using improved grey incidence approach. Energy 2008;33:1427–37.
[77] Pilavachi PA, Roumpeas CP, Minett S, Afgan NH. Multi-criteria evaluation for CHP system options. Energy Conversion and Management 2006;47:3519–29.
[78] Liposcak M, Afgan NH, Duic N, da Graca Carvalho M. Sustainability assessment of cogeneration sector development in Croatia. Energy 2006;31: 2276–84.
[79] Chatzimouratidis AI, Pilavachi PA. Objective and subjective evaluation of power plants and their non-radioactive emissions using the analytic hierarchy process. Energy Policy 2007;35:4027–38.
[80] Chatzimouratidis AI, Pilavachi PA. Multicriteria evaluation of power plants impact on the living standard using the analytic hierarchy process. Energy Policy 2008;36:1074–89.
[81] Chatzimouratidis AI, Pilavachi PA. Sensitivity analysis of the evaluation of power plants impact on the living standard using the analytic hierarchy process. Energy Conversion and Management 2008;49:3599–611.
[82] Beccali M, Cellura M, Mistretta M. Decision-making in energy planning. Application of the electre method at regional level for the diffusion of renewable energy technology. Renewable Energy 2003;28: 2063–87.
[83] Diakoulaki D, Karangelis F. Multi-criteria decision analysis and cost-benefit analysis of alternative scenarios for the power generation sector in Greece. Renewable and Sustainable Energy Reviews 2007;11:716–27.
[84] Cavallaro F, Ciraolo L. A multicriteria approach to evaluate wind energy plants on an Italian island. Energy Policy 2005;33:235–44.
[85] Burton J, Hubacek K. Is small beautiful? A multicriteria assessment of small-scale energy technology applications in local governments. Energy Policy 2007;35:6402–12.
[86] Madlener R, Kowalski K, Stagl S. New ways for the integrated appraisal of national energy scenarios: the case of renewable energy use in Austria. Energy Policy 2007;35:6060–74.
[87] Wang JJ, Jing YY, Zhan CF. Weighting methodologies in multi-criteria evaluations of combined heat and power systems. International Journal of Energy Research, doi:10.1002/er.1528.
[88] Papadopoulos A, Karagiannidis A. Application of the multi-criteria analysis method Electre III for the optimisation of decentralised energy systems. Omega 2008;36:766–76.
[89] Goumas MG, Lygerou VA, Papayannakis LE. Computational methods for planning and evaluating geothermal energy projects. Energy Policy 1999;27:147–54.
[90] Haralambopoulos DA, Polatidis H. Renewable energy projects: structuring a multi-criteria group decision-making framework. Renewable Energy 2003;28:961–73.
[91] Alanne K, Salo A, Saari A, Gustafsson S-I. Multi-criteria evaluation of residential energy supply systems. Energy and Buildings 2007;39:1218–26.
[92] Løken E, Botterud A, Holen AT. Use of the equivalent attribute technique in multi-criteria planning of local energy systems. European Journal of Operational Research 2009;197:1075–83.
[93] Prindle B, Eldridge M, Eckhardt M, Frederick A. The twin pillars of sustainable energy: synergies between energy efficiency and renewable energy technology and policy; American Council for an Energy Efficient Economy, ACEEE Report number E074, Washington DC, 2007.
[94] Beer JM. High efficiency electric power generation: the environmental role. Progress in Energy and Combustion Science 2007;33:107–34.
[95] Rant Z. Exergie, ein neues Wort fur "Technische Arbeitsfahigkeit Exergy, a new word for "technical available work" Forschung auf dem Gebiete des Ingenieurwesens 1956;22:36–7.
[96] National Petroleum Council. Securing oil and natural gas infrastructures in the new economy; 2001.
[97] McCarthy RW, Ogden JM, Sperling D. Assessing reliability in energy supply systems. Energy Policy 2007;35:2151–62.
[98] Billinton R, Karki R. Reliability/cost implications of utilizing photovoltaics in small isolated power systems. Reliability Engineering & System Safety 2003;79:11–6.
[99] Kiehl JT, Trenberth KE. Earth's annual global mean energy budget. Bulletin of the American Meteorological Society 1997;78:197–208.
[100] Holleman AF, Wiberg E. Inorganic chemistry. San Diego: Academic Press; 2001.
[101] Lamminen E, Isherwood H. Comparison of fine particle emissions from a modern small-scale biomass boiler and from a large-scale coal-firing power plant. In: European Aerosol Conference; 2007.
[102] Wierzbicka A, Lillieblad L, Pagels J, Strand M, Gudmundsson A, Gharibi A, et al. Particle emissions from district heating units operating on three commonly used biofuels. Atmospheric Environment 2005;39:139–50.
[103] Bond TC, Bussemer M, Wehner B, Keller S, Charlson RJ, Heintzenberg J. Light absorption by primary particle emissions from a lignite burning plant Environmental Science and Technology 1999;33:3887–91.
[104] Zahnd A, Kimber HM. Benefits from a renewable energy village electrification system. Renewable Energy 2009;34:362–8.
[105] Ye YC, Ke LH, Huang DY. System synthetical evaluation technology and its application. Beijing: Metallurgical Industry Press; 2006.
[106] Jin J, Wei YM. Generalized intelligent assessment methods for complex systems and applications. Beijing: Science Press; 2008.
[107] Guo YJ. System synthetical evaluation theory, methods and application. Beijing: Science Press; 2007.
[108] Rowe G, Wright G. Expert opinions in forecasting: role of the delphi technique. In: Armstrong, editor. Principles of forecasting: a handbook of researchers and practitioners. Boston: Kluwer Academic Publishers; 2001.
[109] Shen ZY, Yang ZF. Gray associate analysis method in screening of index system. Mathematics in Practice and Theory 2002;32:728–32.
[110] Li CM, Ding LY. Slection criteria methods of complex system. Statistics and Decision 2004;177:8–9.
[111] Xu H, Luo C, Liu ZG. Study on the selection method of evaluation indexes by AHP. China Offshore Oil and Gas 2007;19:415–8.
[112] Gao J, Sun LY, Li MY. Range estimation priority: a method to sift out weak-weighted criteria in AHP. Systems Engineering—Theory & Practice 2005; 25:73–7.
[113] Wang YL. Systems engineering, 2nd ed., Beijing: Mechanical industry press; 2001
[114] Jia JM, Fisher GM, Dyer JS. Attribute weighting methods and decision quality in the presence of response error: a simulation study. Journal of Behavioral Decision Making 1998;11:85–105.
[115] Dawes RM, Corrigan B. Linear models in decision making. Psychological Bulletin 1974;81:95–106.
[116] Pöyhönen M, Hämäläinen RP. On the convergence of multiattribute weighting methods. Theory and Methodology 2001;129:569–85.
[117] Weber M, Borcherding K. Behavioral influences on weight judgments in multiattribute decision making. European Journal of Operational Research 1993;67:1–12.
[118] Edwards W. How to use multiattribute utility measurement for social decision making. IEEE Transactions on Systems Man and Cybernetics 1977;SMC–7:326–40.
[119] Edwards W, Barron FH. Smarts and smarter: improved simple methods for multiattribute utility measurement. Organizational Behavior and Human Decision Processes 1994;60:306–25.
[120] von Winterfeldt D, Edwards W. Decision analysi and behavioral research. London: Cambridge University Press; 1986.
[121] Simos J. Evaluer l'impact sur l'environnement: Une approche originale par l'analyse multicritère et la négociation. Lausanne: Presses Polytechniques et Universitaires Romandes; 1990.
[122] Saaty TL. Modeling unstructured decision problems: a theory of analytical hierarchies. In: Proceedings of the first international conference on mathematical modeling. University of Missoure Rolla; 1977.
[123] Saaty TL. The analytic hierarchy process. New York, NY, USA: McGraw-Hill; 1980
[124] Xu JP, Wu W. Multiple attribute decision making theory and methods. Beijing: Tsinghua University Press; 2006.
[125] Saaty TL. A scaling method for priorities in hierarchical structures. Journal of Mathematical Psychology 1978;1:57–68.
[126] Hwang CL, Yoon K. Multiple attribute decision making-methods and application: a state-of-the-art survey. New York, USA: Springer-Verlag; 1981.
[127] Jaber JO, Jaber QM, Sawalha SA, Mohsen MS. Evaluation of conventional and renewable energy sources for space heating in the household sector. Renewable and Sustainable Energy Reviews 2008;12:278–89.
[128] Kahraman C. Fuzzy multi-criteria decision making: theory and applications with recent developments. US: Springer; 2008.
[129] Lin Y, Liu S. A historical introduction to grey systems theory. In: Proceedings of the 2004 IEEE international conference on systems, man and cybernetics. Hague, the Netherlands: Institute of Electrical and Electronics Engineers Inc.; 2004
[130] Zadeh LA. Fuzzy sets. Information and Control 1965;3:338–53.
[131] Cengiz K. Fuzzy multi-criteria decision making. Springer; 2008.
[132] Benayoun R, Roy B, Sussman N. Manual de reference du programme electre. Pairs: Direction Scientifiques SEMA; 1966.
[133] Roy B. Classement et choix en presence de points de vue multiples. La methode ELECTRE RIRO 1968;8:57–75.
[134] Roy B. ELECTRE III: Un algorithme de classements fonde sur une representation floue des preference en presence de criteres multiples. Cahiers de CERO 1978;20:3–24.
[135] Roy B, Bertier P. La methode ELECTRE II: Une methode au media-planning. Amsterdam: North-Holland; 1973.
[136] Brans JP, editor. Operational research'84. Amsterdam: North-Holland; 1984.
[137] Conitzer V. Computational aspects of preference aggregation. Pittsburgh: Computer Science Department, Carnegie Mellon University; 2006.
[138] Yi PT, Guo YJ, Zhang DN. Combination bargaining method for multi-evaluation conclusions characterized by disagreement. Journal of Northeastern University (Natural Science) 2006;27:1389–92.
[139] Yi PT, Guo YJ. A method of multi-evaluation conclusions bargaining combination under the feature of conflict between two parties. Systems Engineering—Theory & Practice 2006;26:63–72.